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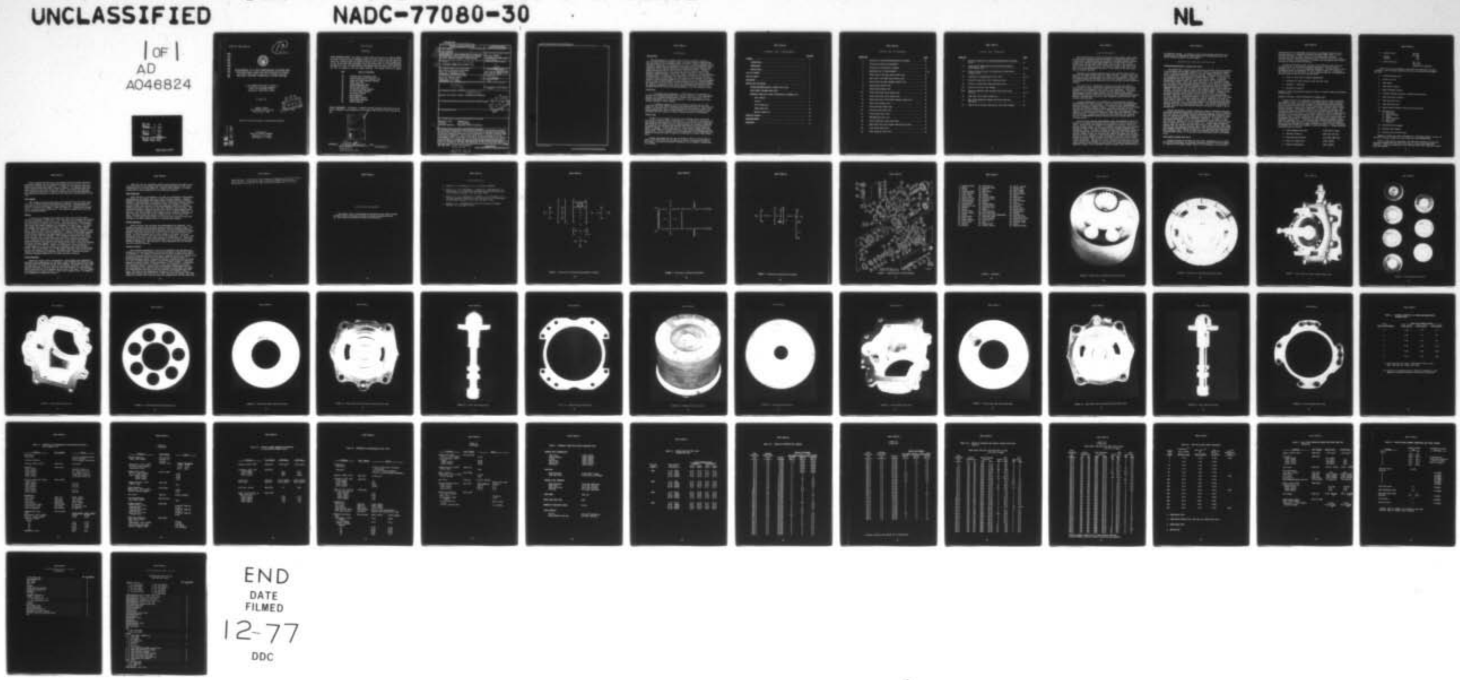

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DEVELOPMENT OF A HIGH TEMPERATURE SILICONE BASE FIRE-RESISTANT FLUID FOR APPLICATION IN FUTURE MILITARY AIRCRAFT HYDRAULIC SYSTEM DESIGNS

J. Lee Hammond and Alfeo A. Conte, Jr.
Air Vehicle Technology Department
NAVAL AIR DEVELOPMENT CENTER
Warminster, Pennsylvania 18974

15 JUNE 1977

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Prepared for
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A candidate silicone-base fire-resistant hydraulic fluid designated Nadraul MS-6 has been developed for future military aircraft hydraulic system design. A 500 hour hydraulic pump-loop circuit evaluation of the MS-6 fluid has been successfully completed. Data on this phase of the investigation and the development effort on the MS-6 fluid and an alky-ester siloxane are reported. A design guide is planned based on the physical and chemical properties of MS-6 so that future hydraulic systems can be designed around the properties of this new formulation and thus take advantage of its fire-resistant nature.

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SUMMARY

INTRODUCTION

The development of a superior fire-resistant hydraulic fluid for use in current military aircraft without requiring retrofit modifications has been shown to be a formidable task. In order to achieve superior fire-resistance properties in a candidate fluid, other critical properties such as viscosity, density and bulk modulus will probably be quite different when compared to the currently used petroleum fluid (MIL-H-5606). Because of these differences, the new fluid will not function properly in current hydraulic system designs. New fluids which are similar to 5606 in basic physical properties usually offer only slight improvements in fire-resistance characteristics. Accordingly, the major thrust of this program has been directed toward the development of a military aircraft hydraulic fluid with excellent fire-resistance capabilities suitable for use at operating temperatures as high as 478°K (400°F) in future aircraft hydraulic system designs. Our intent is to provide such a fluid with completely characterized chemical and physical properties so that future aircraft hydraulic systems can be designed around this fluid and take advantage of its fire-resistant nature.

CONCLUSIONS

1. A candidate high temperature (478°K (400°F)) fire-resistant hydraulic fluid designated Nadraul MS-6 has been developed. This formulation consists of a tetrachlorophenylmethyl siloxane fluid containing 4 wt. % dibutyl chlorendate as an antiwear additive. It was developed for future aircraft hydraulic system designs.

2. A hydraulic pump-loop circuit evaluation conducted at 20.7 MPa (3000 PSI) and 422°K (300°F) average fluid temperature for 500 hours was completed. No unusual wear or fluid deterioration was observed. Some of the pump components were found to have deposits or corrosion products on their surfaces, the exact nature or origin of which has yet to be determined.

FUTURE PLANS

Efforts in this program will center on developing design guide data on a 30 dm^3 (8 gallon) batch of Nadraul MS-6. In addition to evaluation for specification type properties, this batch of fluid will be used to generate data which are not usually found in specifications for hydraulic fluids but are essential for the design and analysis work involved on developing new hydraulic systems. These properties will include heat transfer characteristics, bulk modulus, viscosity-pressure curves, density-temperature curves among others. Also an evaluation of fluid performance in a 55 MPa (8000 PSI) hydraulic system test stand is planned in addition to a 478°K (400°F) pump test.

Further investigations into the corrosion of steel in the presence of water in the MS-6 fluid will be made in an effort to determine its nature and origin. In addition, effective inhibitors will be sought if indeed they are required.

TABLE OF CONTENTS

Page No.

SUMMARY 1

INTRODUCTION 1

CONCLUSIONS 1

FUTURE PLANS 1

LIST OF FIGURES 3

LIST OF TABLES 4

BACKGROUND 5

RESULTS AND DISCUSSION 6

TETRACHLOROPHENYLMETHYL SILOXANE BASE FLUID 6

ALKYL-ESTER SILOXANE BASE FLUID 6

HYDRAULIC PUMP-LOOP CIRCUIT EVALUATION OF NADRAUL MS-6 7

Seal Leakage 9

Filters 9

Fluid Properties 9

Pump Inspection 10

System Inspection 10

CORROSION ASPECTS 10

ACKNOWLEDGEMENT 12

REFERENCES 13

LIST OF FIGURES

Figure No.		Page
1	Structure of Tetrachlorophenylmethyl Siloxane	14
2	Structure of Dibutyl Chlorendate	15
3	Structure of Alkyl-Ester Siloxane	16
4	Exploded View of Pump Assembly	17,18
5	Front View of Cylinder Block Before Test	19
6	Rear View of Cylinder Block Before Test	20
7	Drive Shaft and Yoke Assembly Before Test	21
8	Piston Shoes Before Test	22
9	Pump Housing Before Test	23
10	Piston Hold Down Plate Before Test	24
11	Piston Shoe Wear Plate Before Test	25
12	Pump Valve Plate with Needle Bearing Before Test	26
13	Pilot Valve Before Test	27
14	Plate Retainer Before Test	28
15	Cylinder Block After Test	29
16	Piston Shoes After Test	30
17	Pump Housing After Test	31
18	Piston Shoe Wear Plate After Test	32
19	Pump Valve Plate with Needle Bearing After Test	33
20	Pilot Valve After Test	34
21	Plate Retainer After Test	35

LIST OF TABLES

Table No.		Page
I	Antiwear Properties of Tetrachlorophenylmethyl Siloxane Fluid	36
II	Properties of Experimental Fire-Resistant Hydraulic Fluid Nadraul MS-6	37,38
III	Effect of Ester Content on Properties of Alkyl-Ester Siloxane Fluid	39
IV	Properties of Experimental Fluid "750"	40,41
V	Hydraulic Pump-Loop Circuit Operating Data	42
VI	Pretest and Post-Test Pump Calibration Data	43
VII	Record of Actuator Seal Leakage	44,45
VIII	Record of Pressure Drop Across Filters After Each Start Up	46,47
IX	Pump Test Fluid Sample Properties	48
X	MS-6 Fluid Properties Before and After Pump Test Evaluation	49
XI	Pump Friction Element Dimensional and Weight Changes	50

BACKGROUND

The susceptibility of military aircraft to fire hazards under combat or operational conditions greatly diminishes an effective strike force. A particularly vulnerable area can be found in aircraft hydraulic systems in which the operating fluid (MIL-H-5606) has a flash point of 372°K (210°F) which is only 39°K (70°F) higher than jet fuel. The exposure of this fluid to an ignition source as a result of enemy ground fire, accidents or system malfunctions represents a real threat to the safe operation of military aircraft.

Hydraulic fluid induced aircraft fires have occurred and are documented by the Naval Safety Center for naval aircraft. In many cases total aircraft and crew have been lost as a result of such incidents. This loss of weapons systems and personnel could have been eliminated if suitable fire-resistant fluids were developed for use in military aircraft hydraulic systems.

The search for a nonflammable hydraulic fluid has been going on for at least 25 years. Since 1958, commercial aircraft have been using a phosphate ester hydraulic fluid which is fire-resistant. This fluid, however, is not suitable for military aircraft applications. Hydraulic fluids based on super refined mineral oil and synthetic hydrocarbon (MIL-H-83282) base oils have been developed and are commercially available. However, although these fluids are less flammable than MIL-H-5606, they are not fire-resistant.

A major breakthrough in the search for a fire-resistant military aircraft hydraulic fluid occurred in 1968 with discovery of suitable antiwear additives for silicone fluids. This resulted from a NAVAIRDEVCEN in-house independent research program. Silicone fluids had been considered for military aircraft hydraulic system applications because of their superior fire-resistance properties. However, one shortcoming was their inability to lubricate metal components, especially under boundary lubricating conditions. A patent was issued in 1971 (reference (1)) covering the use of NAVAIRDEVCEN developed antiwear additives (polysulfides) in silicone fluids.

Based on these findings NAVAIRSYSCOM tasked NAVAIRDEVCEN in FY-69 to develop a fire-resistant hydraulic fluid suitable for future military aircraft. During FY-72, the program was redirected to provide a fluid for present aircraft usage. In FY-73, a candidate silicone base fire-resistant aircraft hydraulic fluid was developed and was designated NADRAUL MS-5, references 2 and 3. In order to obtain superior fire-resistance properties certain "trade-offs" had to be considered. Basically MS-5 fluid differs from MIL-H-5606 in that the viscosity and density are higher and the bulk modulus is lower. Because of these differences, a flight control simulator evaluation was performed to assess the effect of MS-5 on critical flight control parameters. The results of this investigation have led to the following conclusions. Because of viscosity, density and bulk modulus differences relative to MIL-H-5606, the use of MS-5 in current military aircraft hydraulic systems is not considered feasible without major modifications to

the hydraulic system. In January of FY-74, this program reverted to its original goal of developing a high temperature fire-resistant fluid for future aircraft hydraulic system designs.

RESULTS AND DISCUSSION

TETRACHLOROPHENYLMETHYL SILOXANE BASE FLUID

The Nadraul MS-5 silicone fluid formulation, although possessing improved fire-resistance and antiwear properties, was limited to application temperatures not greater than 408°K (275°F) due to the thermal instability of the sulfur containing thiadiozole antiwear additive. Therefore, MS-5 could not be considered as a high temperature (478°K (400°F)) fluid. In addition, it was determined that the supplier of the base fluid in MS-5, a dichlorophenylmethyl siloxane fluid, had taken this product off the market because of low volume usage. Faced with these obstacles, it was decided to investigate the use of a tetrachlorophenylmethyl siloxane fluid which had previously been considered in the retrofit program but was rejected because it would immediately precipitate the viscosity-index improver found in MIL-H-5606 when admixed. This fluid, which is used in the constant speed drives on the A-4 aircraft, is covered by Military Specification MIL-S-81087A. Because of the increased chlorine content relative to the dichloro fluid, the inherent antiwear properties are improved; however, the use of an antiwear additive was still required. Dibutylchlorendate, formerly designated "CCD", was found to provide the desired antiwear qualities even at temperatures as high as 478°K (400°F) (Table I). The optimum formulation resulting from this investigation contained 4 wt. % dibutylchlorendate in the tetrachlorophenylmethyl siloxane fluid and is designated Nadraul MS-6. The chemical structures of the base silicone fluid and antiwear additive are given in Figures 1 and 2, respectively.

Having established a suitable formulation based on antiwear properties, additional property determinations were made and these are listed in Table II. As can be seen in this Table, the MS-6 formulation appears to be quite suitable for continuous operating temperatures as high as 478°K (400°F) in addition to offering superior fire-resistance properties. In regard to fire-resistance evaluations, some of the tests performed on MS-5 have not been done for MS-6. However, it is not unreasonable to assume that the MS-6 fluid will be equivalent to MS-5 in these tests, i.e., linear flame propagation, oxygen index, hot manifold drip and high pressure spray ignition, mist flash back and gun fire testing (reference (2)). Also, the bulk modulus and streaming potential characteristics are expected to be substantially equivalent to MS-5 (reference (2)). The MS-6 fluid is not miscible with small quantities of MIL-H-5606, however, it is miscible with MIL-H-83282 fluid in all proportions.

ALKYL-ESTER SILOXANE BASE FLUID

Another siloxane fluid which has been under investigation is an alkyl-ester modified siloxane, the chemical structure of which is given in Figure 3. Because of the highly organic nature of this molecule, its solubility

characteristics are appreciably better than conventional siloxanes and it has been found to be completely miscible with MIL-H-5606 fluid. By controlling the amount of ester units in the siloxane chain, distinct viscosity and fire-resistance properties can be obtained as shown in Table III. The viscosity can be observed to increase with increasing ester content as does its fire-resistance properties.

Initial investigations have centered on the 18% ester base fluid containing 2.5% wt. of an additive package consisting of 4 parts trioctyl phosphate and 1 part tris (2-chloroethyl) phosphite. The properties of this formulation which is designated "750" are listed in Table IV. Comparing the properties of 750 with MS-6, it can be observed that the 750 formulation is not as good as MS-6 in the following tests:

1. Steel on steel wear at higher temperatures
2. Flammability (high pressure spray and wick test)
3. Oxidation - corrosion
4. Hydrolytic stability

Because of these deficiencies relative to MS-6, no further work was performed on this fluid.

HYDRAULIC PUMP-LOOP CIRCUIT EVALUATION OF NADRAUL MS-6

A major criteria for determining the capability of a fluid to function as a hydraulic fluid is its ability to lubricate hydraulic pump components. Laboratory screening techniques designed to determine the antiwear properties of fluids have shown that the MS-6 formulation possesses significantly improved antiwear properties in comparison to other silicone fluids. Based on these results, a performance evaluation was initiated to determine the lubricating properties of Nadraul MS-6 in an aircraft hydraulic pump under simulated service conditions. The hydraulic pump-loop circuit evaluation was performed on a system simulating the basic functions of the A-4E aircraft hydraulic system. Details concerning the operation of this system along with photographs and schematic diagrams of the test stand have previously been reported (reference (3)). A new Vickers Model PV3-044-3A Variable Displacement "In-Line" Pump was used in this evaluation. Fluorocarbon elastomeric seals were used throughout the pump, actuators and other critical components. An exploded view of the pump assembly is shown in Figure 4. Target operating conditions were as follows:

1.	Pump Discharge Flow Rate	0.250 dm^3/s (4 gpm)
2.	Reservoir Pressure	206.8 kPa (30 PSI)
3.	Pump Discharge Pressure	20.68 MPa (3000 PSI)
4.	Reservoir Temperature	422°K (300°F)
5.	Actuator Temperature	422°K (300°F)

6.	Actuator Cycle	OFF 60s
		ON 240s
	Extend	10s
	Retract	10s
7.	System Operation	ON 7.5h
		OFF 16.5h
		(shutdown on weekends)

A daily log of the performance evaluation was maintained at hourly intervals. The following operating conditions were monitored throughout the test:

1. System Operating Time
2. Actuator Cycles
3. Pump Speed
4. Pump Inlet Pressure
5. Pump Discharge Pressure
6. Actuator Cylinder Pressure, Extended and Retracted
7. Pump Case Drain Pressure
8. Pump Case Drain Flow
9. Pump Discharge Flow
10. System Return Pressure, Before and After Filter
11. Temperature at
    a. Pump Inlet
    b. Pump Discharge
    c. System
    d. Pump Case Drain
    e. Return Line
    f. Reservoir
12. Pump Shaft Seal Leakage
13. Actuator Seal Leakage
14. Pressure Drop Across Filters

Samples of fluid were taken periodically to determine changes, if any, in viscosity, antiwear properties, acid number and wick flammability.

Prior to starting the evaluation, the pump was calibrated by measuring the pump discharge flow and case drain flow at various pump speeds and pressures. After the completion of the 500 hour test, this calibration procedure was repeated.

After accumulating 500 hours of performance under the target conditions previously outlined, the test stand was arbitrarily shut down in order to examine the internal pump components. A summary of the operating conditions which resulted during this test is shown in Table V. No abnormal pump operating conditions were noted during this period. The pretest and post-test pump calibration data shown in Table VI indicated that the pump performance was essentially equivalent to that which was observed at the beginning of this test.

Seal Leakage

Seal leakage rates were monitored on the pump shaft and the three actuators, all of which contained fluoroelastomer packings. The pump shaft seal was noted to be only wetted with fluid during the daily operating period. A record of actuator seal leakage is shown in Table VII. Leakage rates ranged from 1 to 5 ml during the same period. The observed leakage rates were well within acceptable limits.

Filters

A record of the pressure drop across the return line and case drain filters is presented in Table VIII. The case drain filter element was replaced only once during the test at 134.5 hours. This was done not because of pressure buildup but to examine the filter for particulate matter. The pressure drop across this element remained low throughout the entire test. The return line element had to be replaced several times due to high pressure buildup. This element was replaced at 17.5, 45.0, 81.0, 164.0, 236.5, 284.5, 289.5 hours. After the 289.5 hours replacement, this filter element remained in the system until the end of the test (500 hours). Analysis of the debris retained on the filters indicated that approximately half of the material was organic while the other half was inorganic. The inorganic fraction was found to be either metallic iron or iron oxide while the organic fraction was not identified. During the period when the filters had to be frequently replaced, a problem occurred in the four-way directional control valve. This valve is fabricated from two dissimilar metals (aluminum and steel) and was not designed to operate at 422°K (300°F). Because of differences in the coefficient of thermal expansion of the two metals, the elastomeric seal would severely abrade. This is attributed to a design problem associated with the test stand and not the result of fluid action. The organic material found in the filter elements was considered to originate from this valve. After the four-way valve was replaced at 290 hours, no further problems developed.

Fluid Properties

During the course of this investigation, fluid samples were obtained to determine if any degradation was occurring. Table IX shows the results of the analyses which were performed on the fluid samples. The viscosity of the fluid was observed to be within +4.1 mm^2/s of the original viscosity. The wear scar diameter exhibited in the Four Ball Wear Test was observed to be not greater than 0.08 mm from the valve obtained at the start of the test. The acid number was observed to be within +0.036 to -.003 of the original value. No change in wick flammability properties occurred.

After the test was completed, property determinations were made on the bulk fluid after it was drained from the system and compared to the values obtained prior to the test (Table X). Based on these results, it is concluded that no gross degradation of the fluid has occurred.

Pump Inspection

After 500 hours of performance, the pump was disassembled, photographed and dimensions and weights taken on critical friction elements. Table XI summarizes the dimensional and weight changes obtained where they could be measured. Minimal changes were observed on all components with the exception of the cylinder block which increased in weight by 8.3 grams. Figures 5 through 14 show the condition of the pump components before the test while Figures 15 through 21 show most of the same components after the test. The piston shoes shown in Figure 8 had many score lines on each assembly before the test. The other components were found to be in excellent condition. In general, after the test, many of the components had a coating or deposits on them. The exact nature and origin of these deposits is not known. The deposit on the pump housing (Figure 17) could be easily wiped off while the coating on the other components had to be mechanically abraded.

System Inspection

After 295 hours, the actuators were disassembled and inspected. One actuator was found to have an oxide coating inside the cylinder barrel. The barrel was cleaned using glass bead blasting. When the oxide was removed, pit marks were found in the area of piston travel only and followed a certain pattern. The second actuator was found to have an oxide coating but no pit marks. The third actuator had no oxide coating or pit marks. An oxide coating was also found on the fluid side of the accumulator. On the air side the fluid was found to contain small particles of seal material. These components are part of the test stand which have been in service during several different evaluations. The condition of these components prior to the test was not carefully monitored.

CORROSION ASPECTS

The corrosion experienced on some of the components from the pump test prompted an initial investigation into this area based on information reported in reference 4. This paper is concerned with corrosion problems experienced in aircraft systems when halocarbons used as cleaning solvents are trapped in the hydraulic system and hydrolyze in the small amount of water present in MIL-H-5606 hydraulic fluid. Essentially, 100 ml of hydraulic fluid is placed in a jar and 10,000 PPM halocarbon or 10,000 PPM water or both are added and exposed to thermal cycling (room temperature to 377°K (270°F)). Indeed when both halocarbon and water are present a steel strip immersed in the fluid will severely corrode. Similar tests were performed using Nadraul MS-6 as the test hydraulic fluid and the source of halogen (no halocarbon was added). At 10,000 PPM water the steel strip was observed to corrode after the first cycle (16 hours at room temperature, 8 hours at 377°K (220°F)). With no added water present the strip did not corrode even after 10 cycles. The water content of the MS-6 fluid from the pump test averaged about 300 PPM before and

after the test. Further structural testing is in progress to determine if this amount of water is critical and also to determine whether the hydrolysis of the chlorine is coming from the base fluid, the antiwear additive or both.

A C K N O W L E D G M E N T

The authors wish to acknowledge the assistance of Mr. Henry Lee who performed various chemical and physical property determinations and Mr. Paul Ceban who performed the pump test evaluation.

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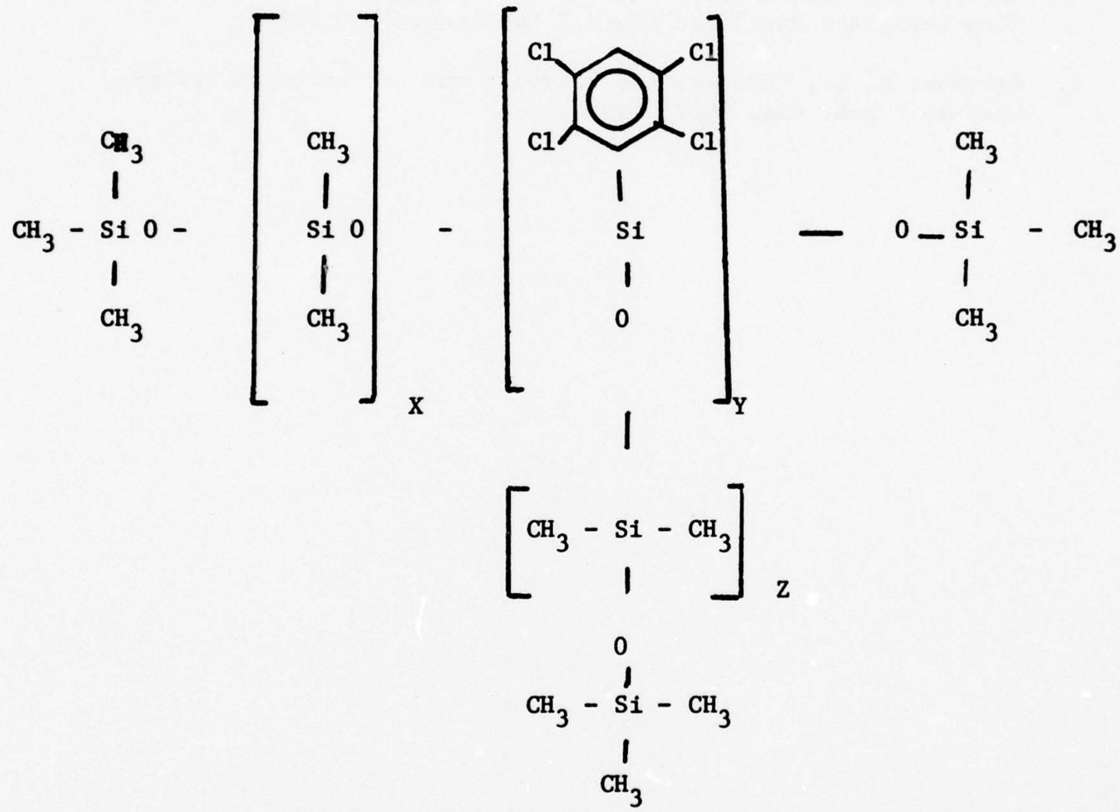

FIGURE 1 - Structure of Tetrachlorophenylmethyl Siloxane

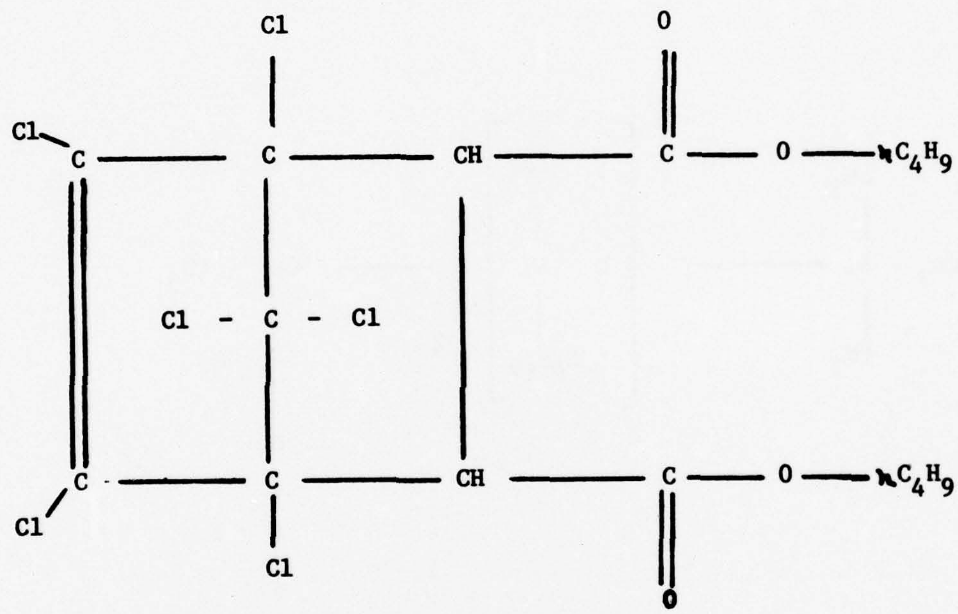

FIGURE 2 - Structure of Dibutyl Chlorendate

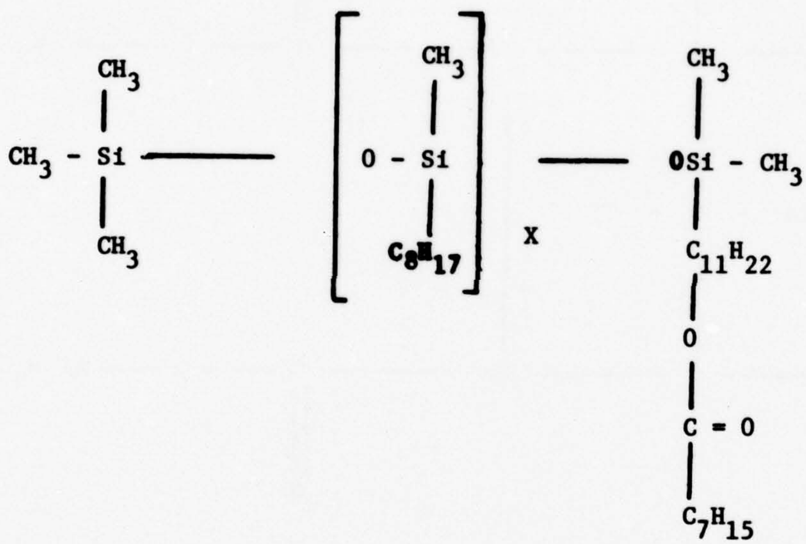

FIGURE 3 - Structure of Alkyl-Ester Siloxane

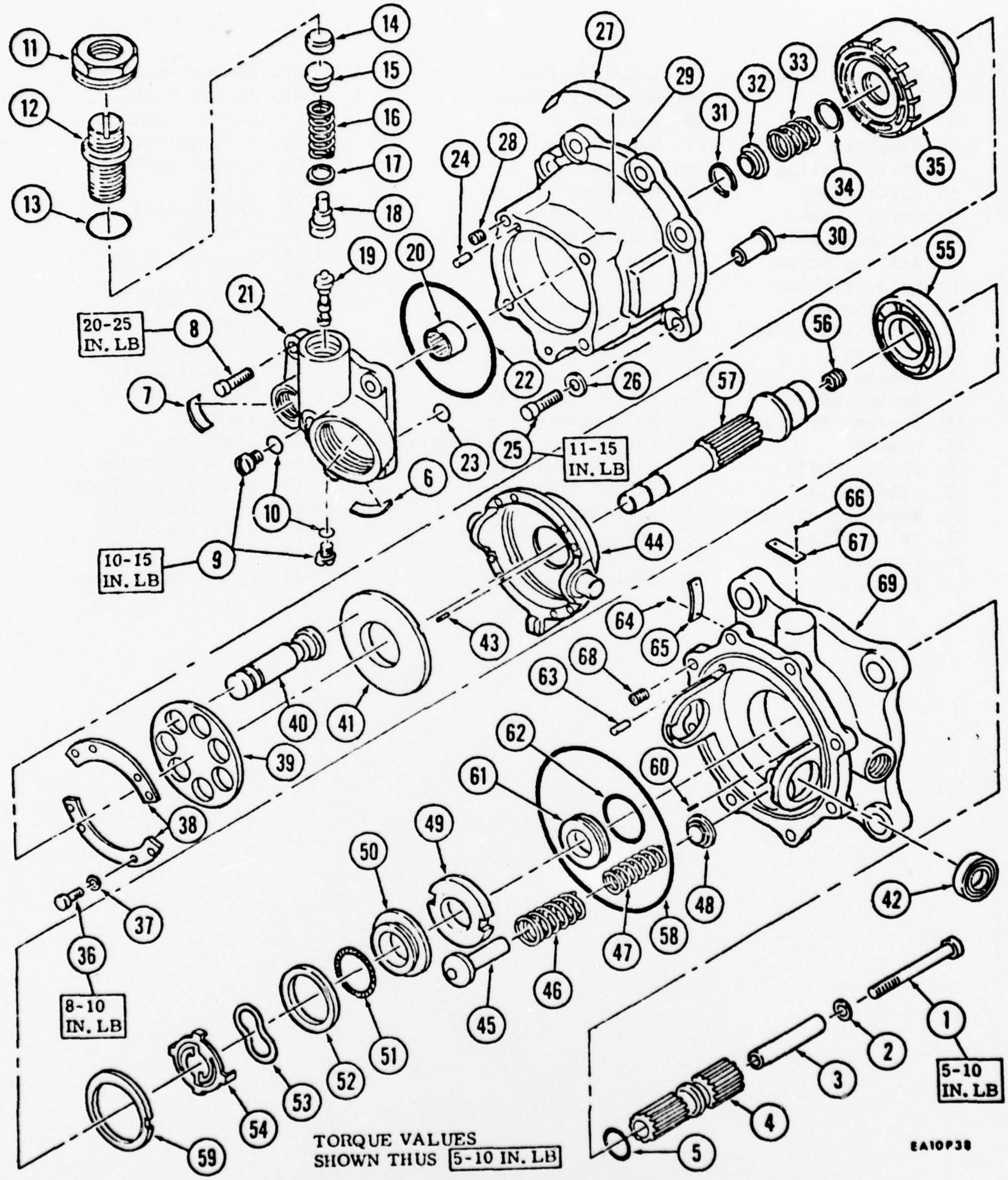

FIGURE 4 - Exploded View of Pump Assembly

1. Mounting Screw
2. Washer
3. Sleeve
4. Coupling Shaft
5. Shaft Packing
6. Inlet Plate
7. Outlet Plate
8. Mounting Screw
9. Sealing Screw
10. Screw Packing
11. Locking Nut
12. Adjusting Screw
13. Packing
14. Spacer
15. Spring Guide
16. Control Spring
17. Washer
18. Spring Guide
19. Pilot Valve
20. Needle Bearing
21. Valve Plate
22. Packing
23. Packing
24. Locating Pin
25. Mounting Screw
26. Washer
27. Name Plate
28. Insert
29. Housing
30. Control Piston
31. Retaining Ring
32. Retainer
33. Spring
34. Spring Spacer
35. Cylinder Block
36. Mounting Screw
37. Washer
38. Plate Retainer
39. Hold Down Plate
40. Piston and Shoe Subassembly
41. Shoe Wear Plate
42. Pintle Bearing
43. Locating Pin
44. Yoke
45. Spring Guide
46. Control Spring
47. Control Spring
48. Spring Seat
49. Carbon Seal
50. Seal grommet
51. Garter Spring
52. Spacer
53. Wave Spring
54. Retainer
55. Shaft Bearing
56. Insert
57. Drive Shaft
58. Packing
59. Thrust Ring
60. Retaining Pin
61. Mating Ring
62. Packing
63. Locating Pin
64. Mounting Screw
65. Instruction Plate
66. Mounting Screw
67. Rotation Plate
68. Insert
69. Mounting Flange

FIGURE 4 - Continued

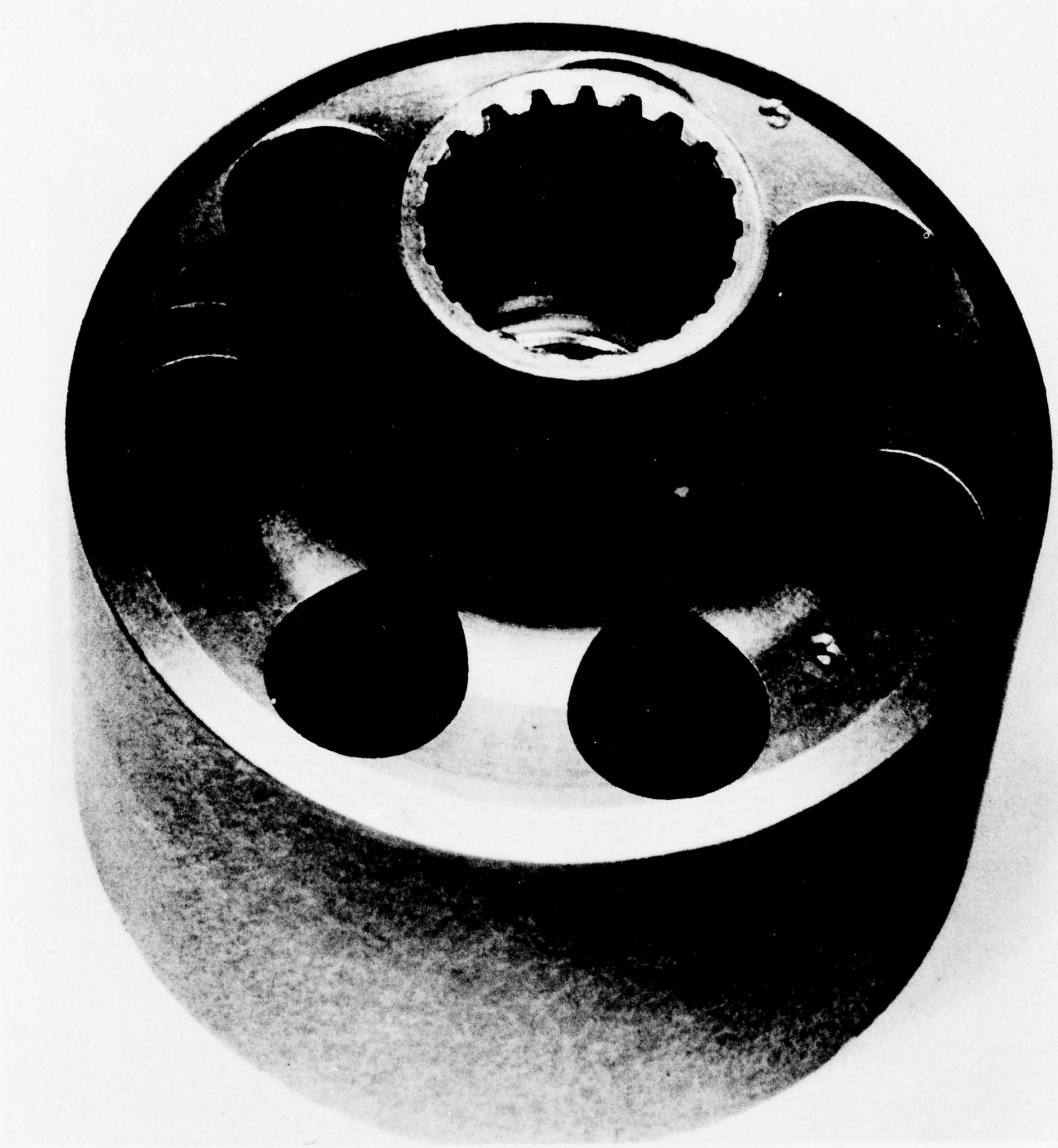

FIGURE 5 - Front View of Cylinder Block Before Test

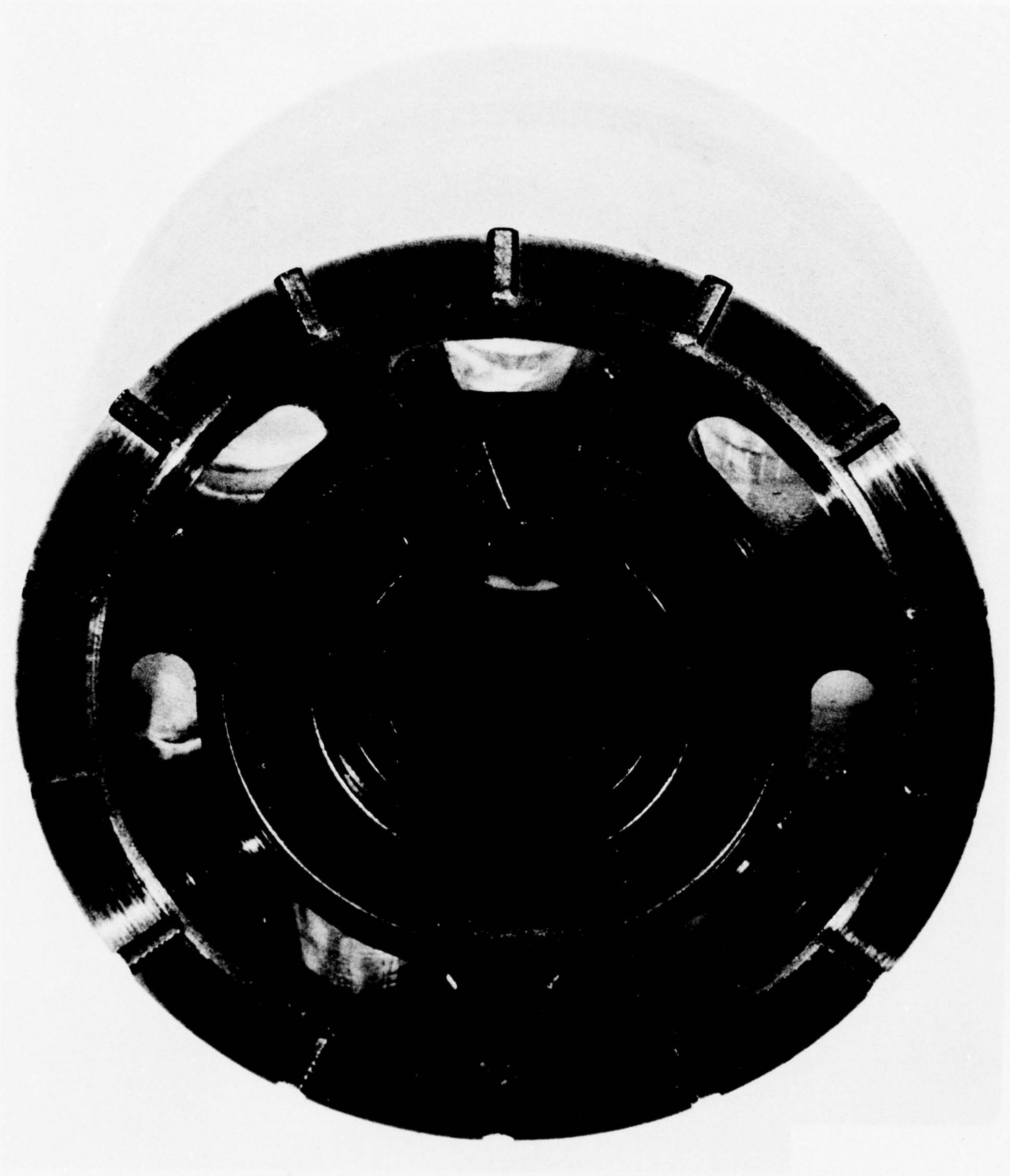

FIGURE 6 - Rear View of Cylinder Block Before Test

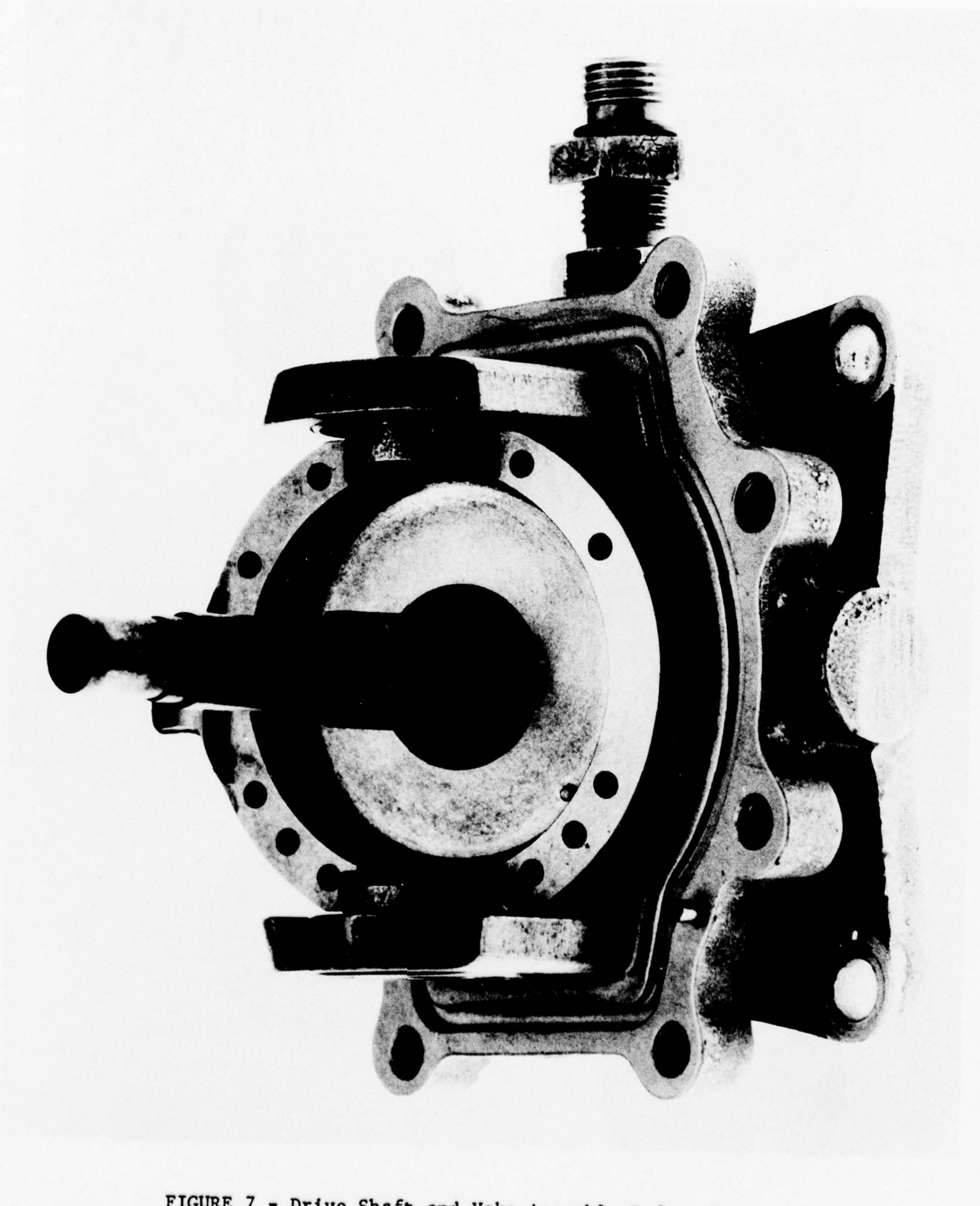

FIGURE 7 - Drive Shaft and Yoke Assembly Before Test

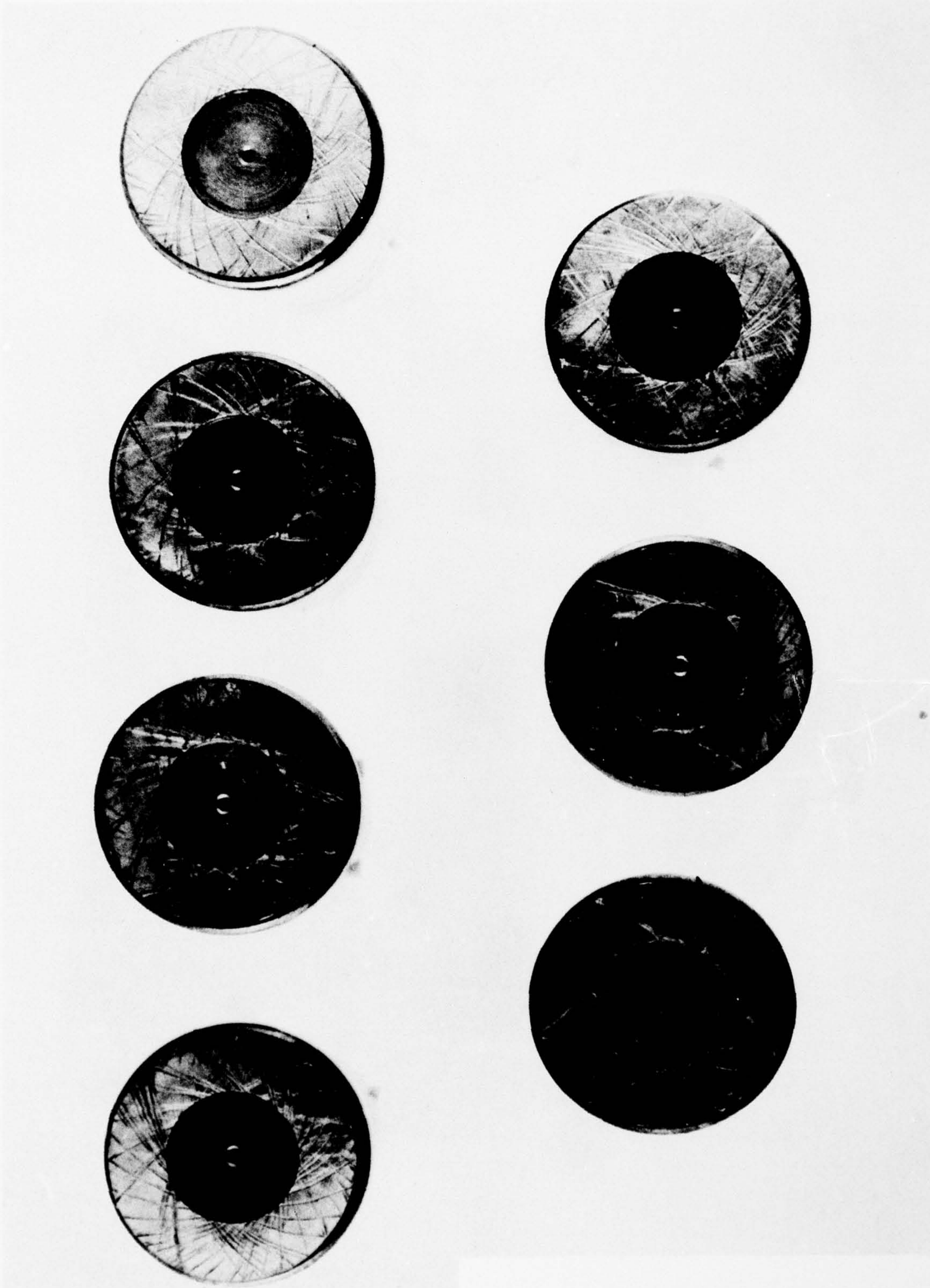

FIGURE 8 - Piston Shoes Before Test

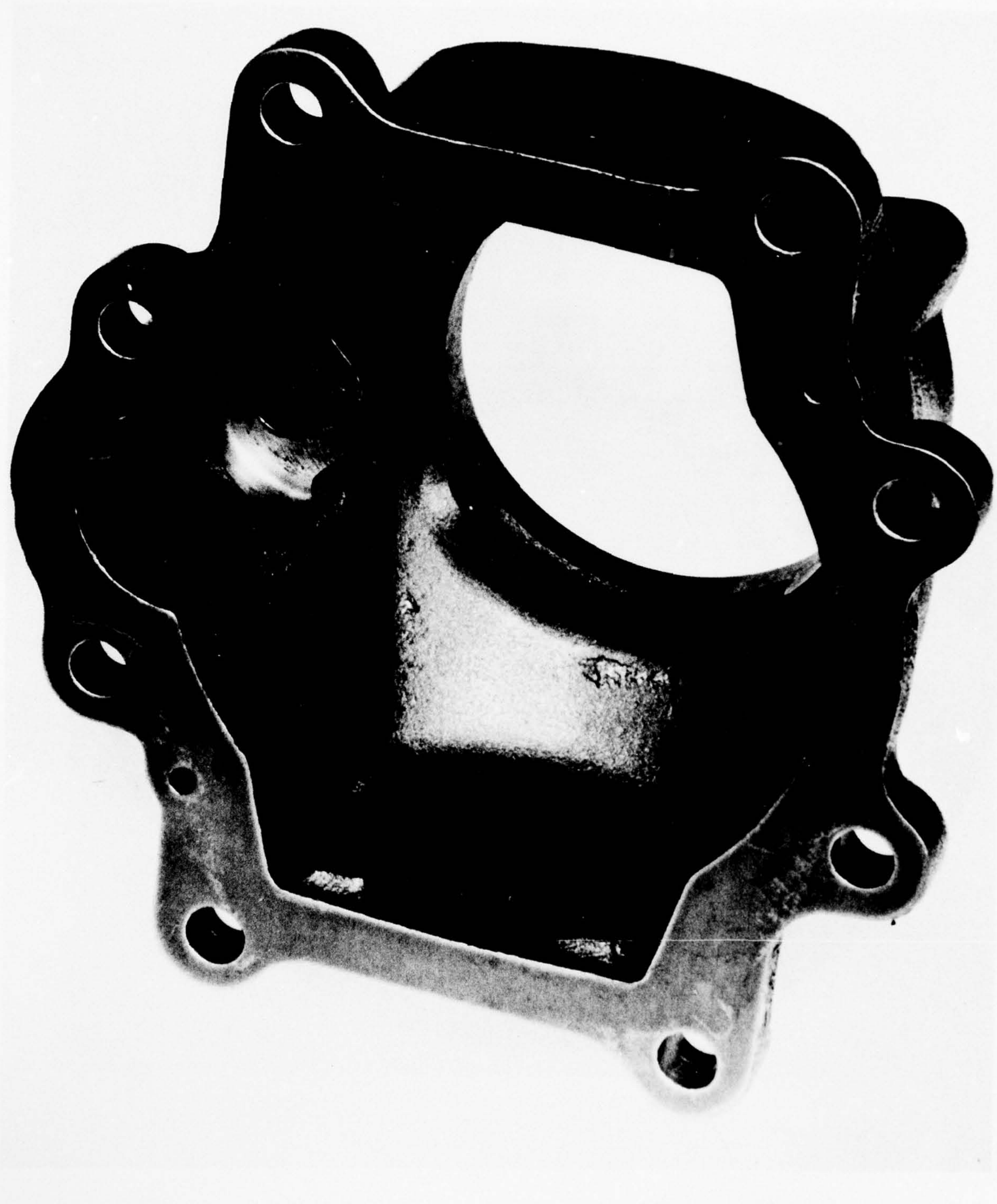

FIGURE 9 - Pump Housing Before Test

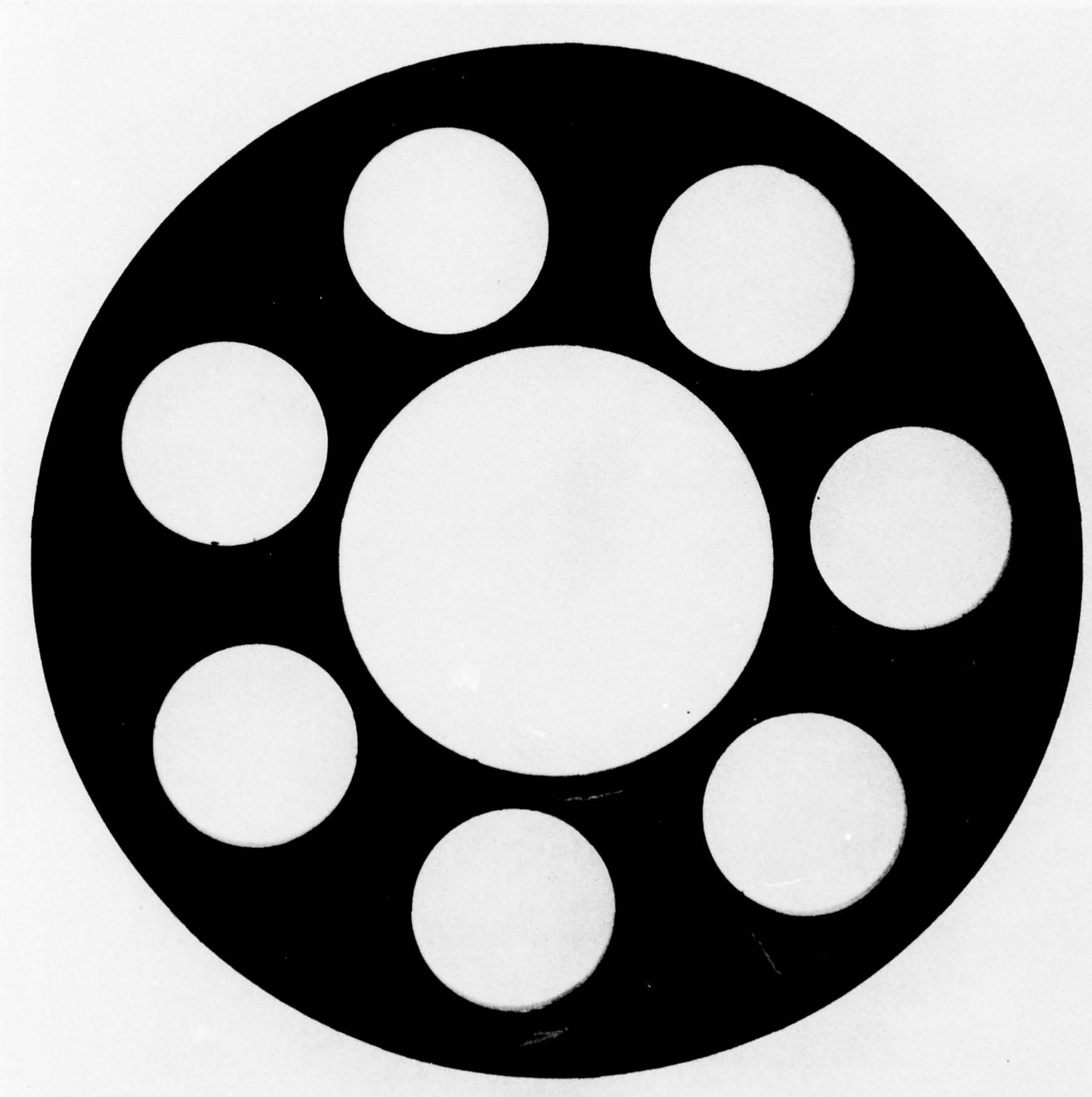

FIGURE 10 - Piston Hold Down Plate Before Test

FIGURE 11 - Piston Shoe Wear Plate Before Test

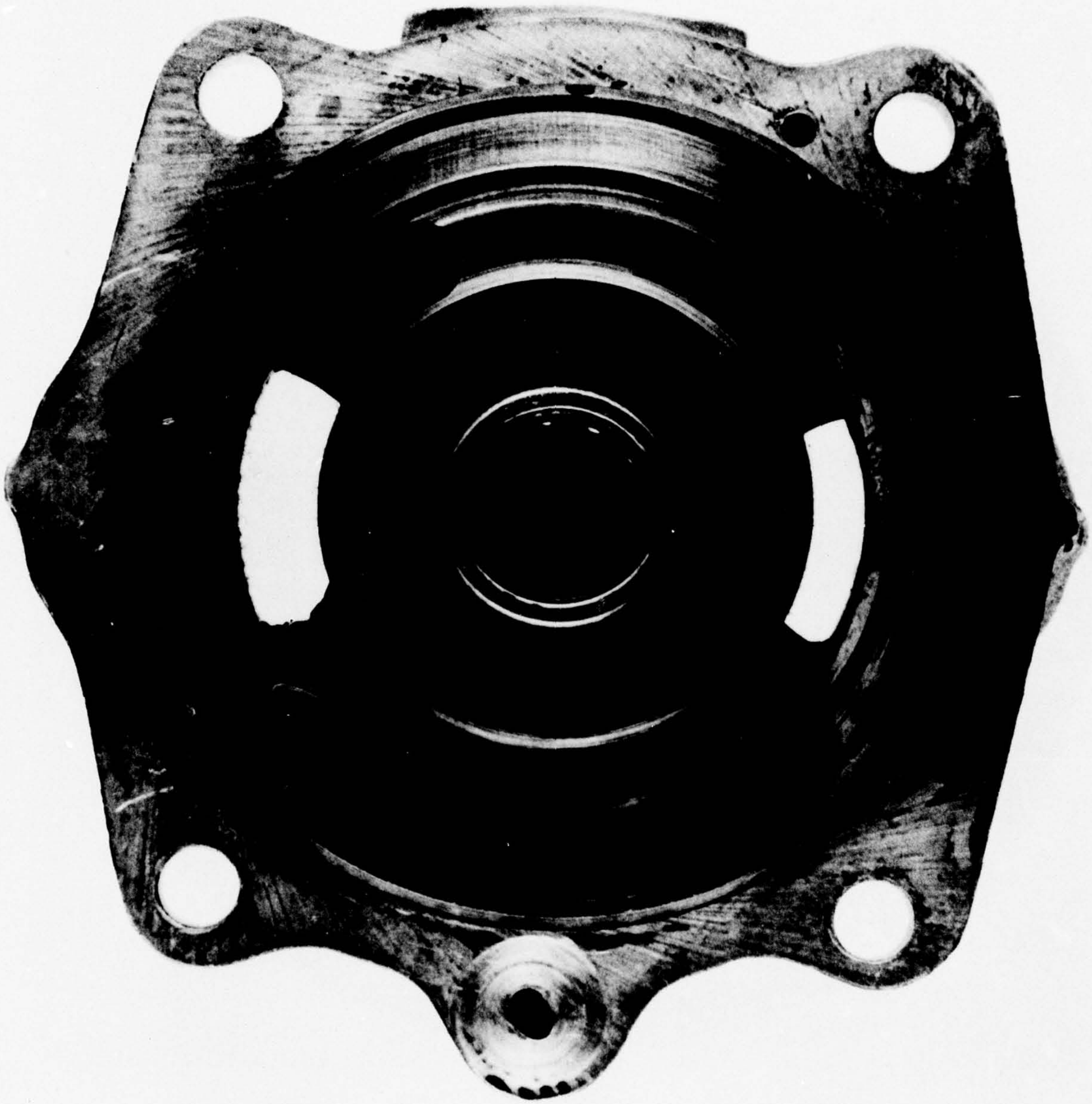

FIGURE 12 - Pump Valve Plate with Needle Bearing Before Test

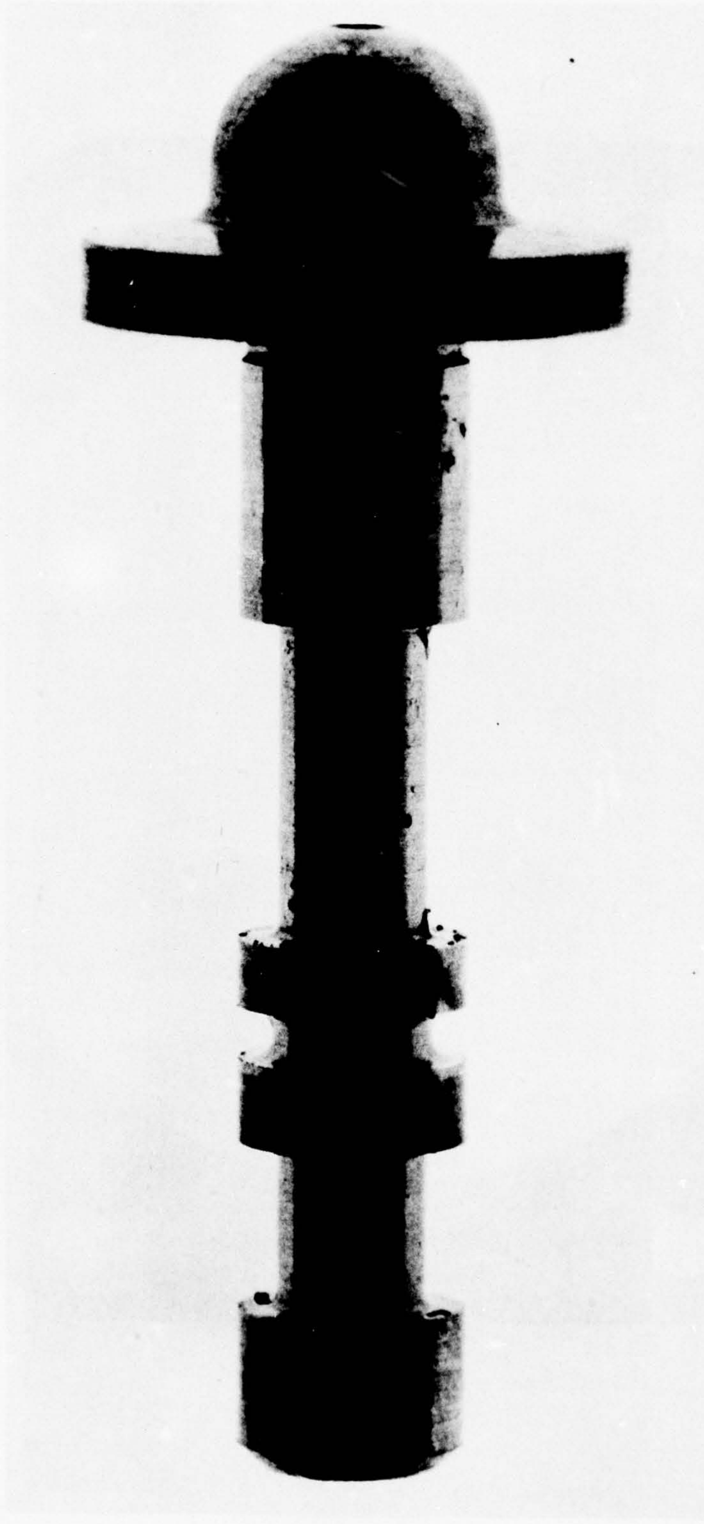

FIGURE 13 - Pilot Valve Before Test

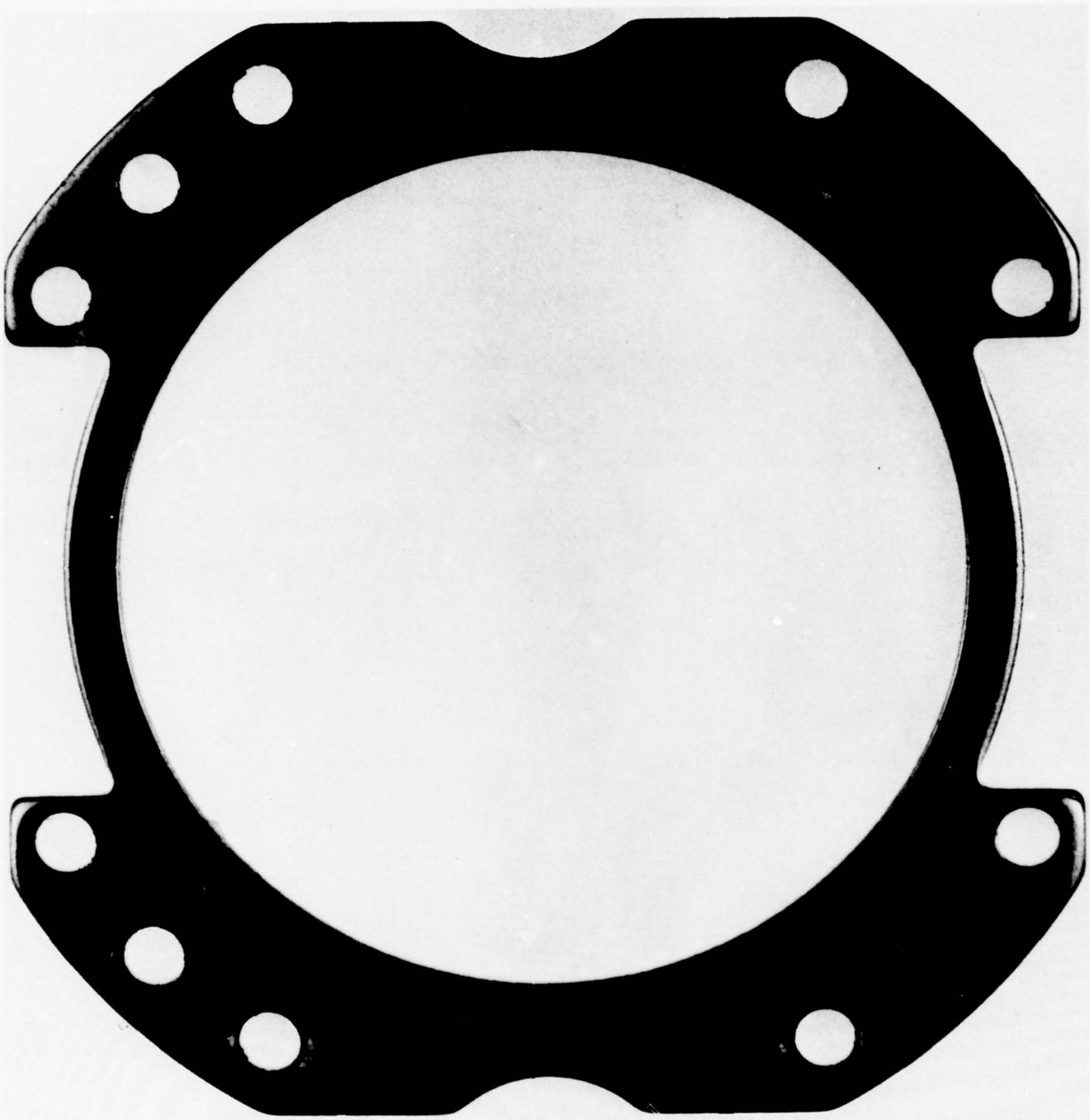

FIGURE 14 - Plate Retainer Before Test

FIGURE 15 - Cylinder Block After Test

FIGURE 16 - Piston Shoes After Test

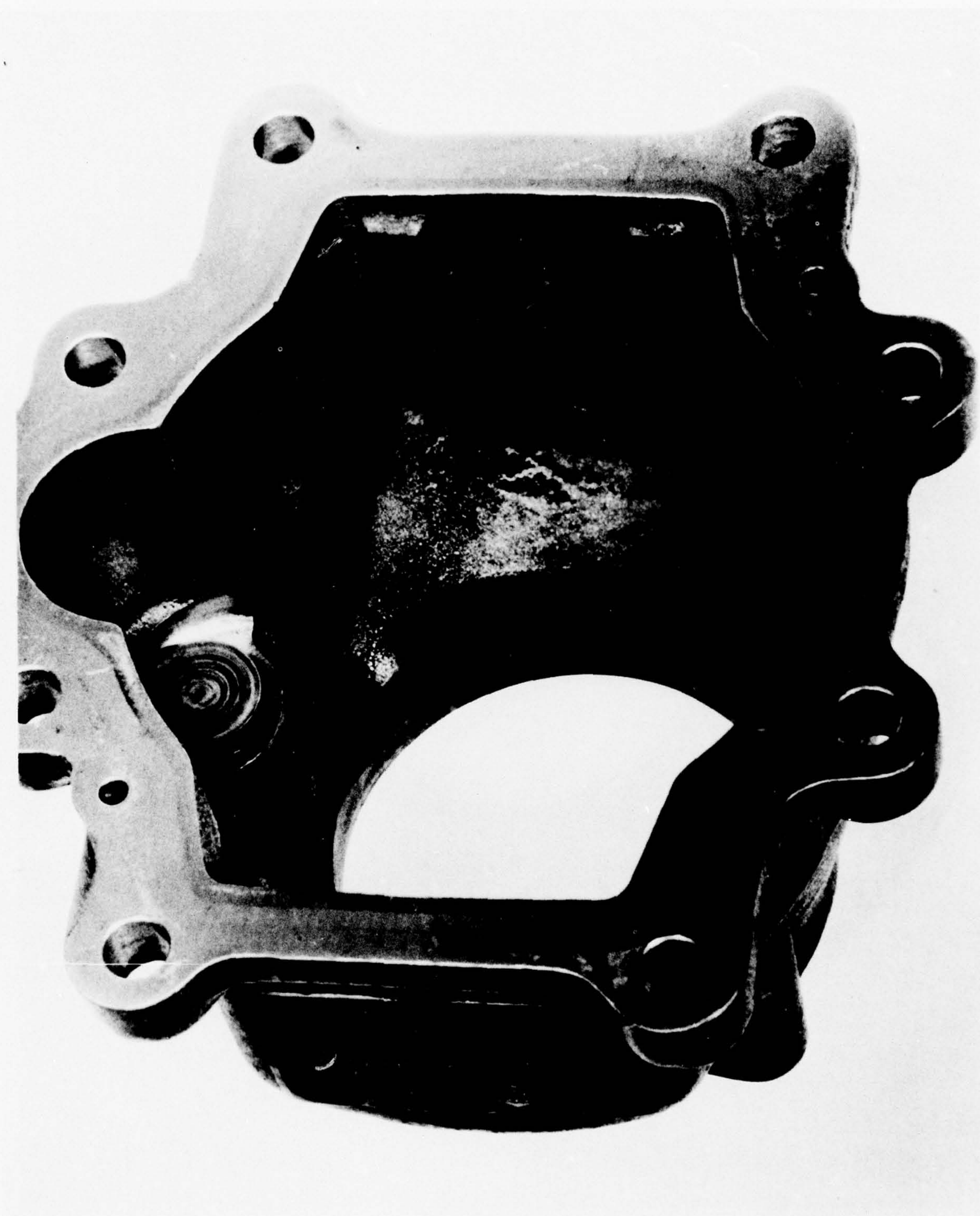

FIGURE 17 - Pump Housing After Test

FIGURE 18 - Piston Shoe Wear Plate After Test

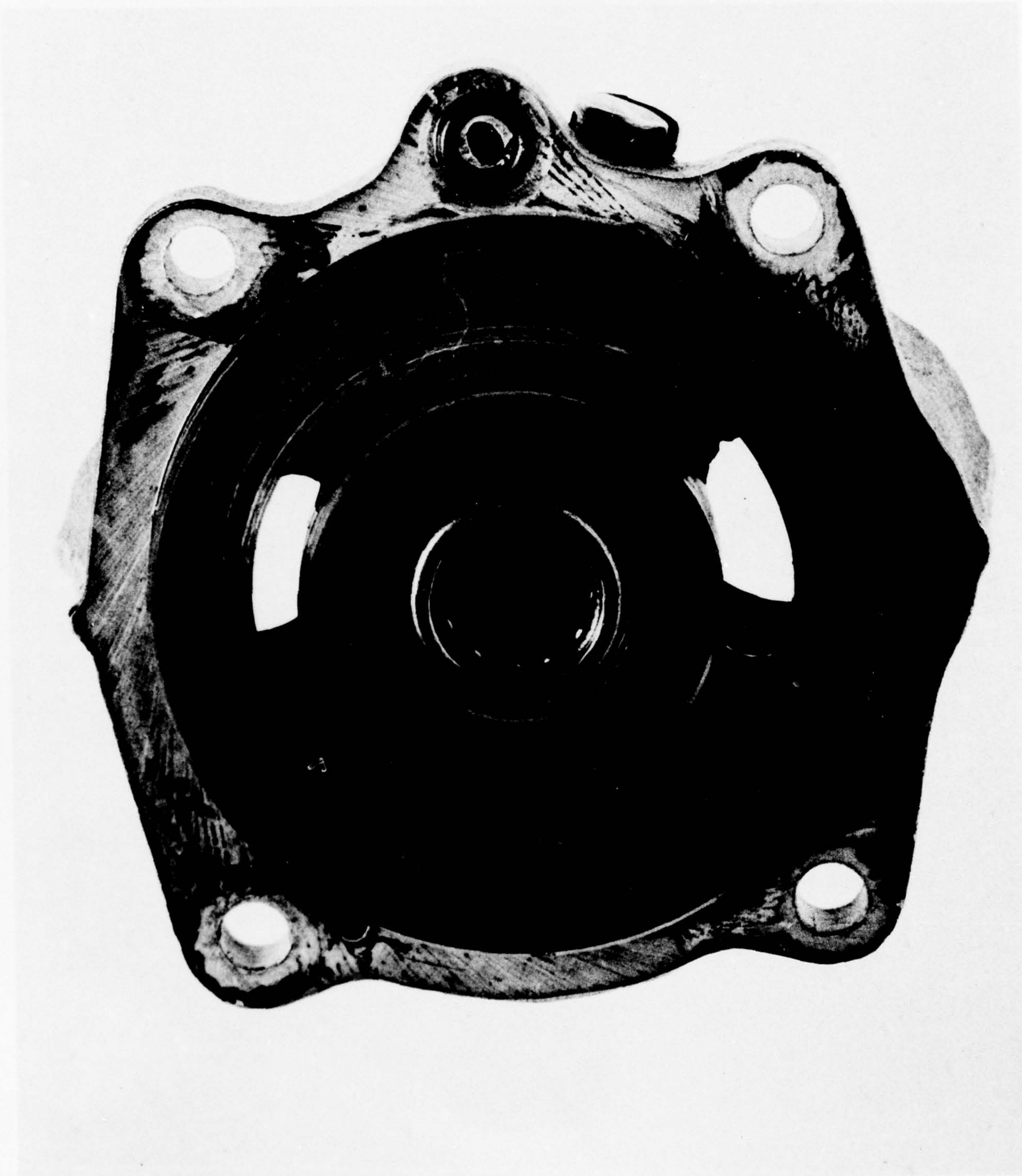

FIGURE 19 - Pump Valve Plate with Needle Bearing After Test

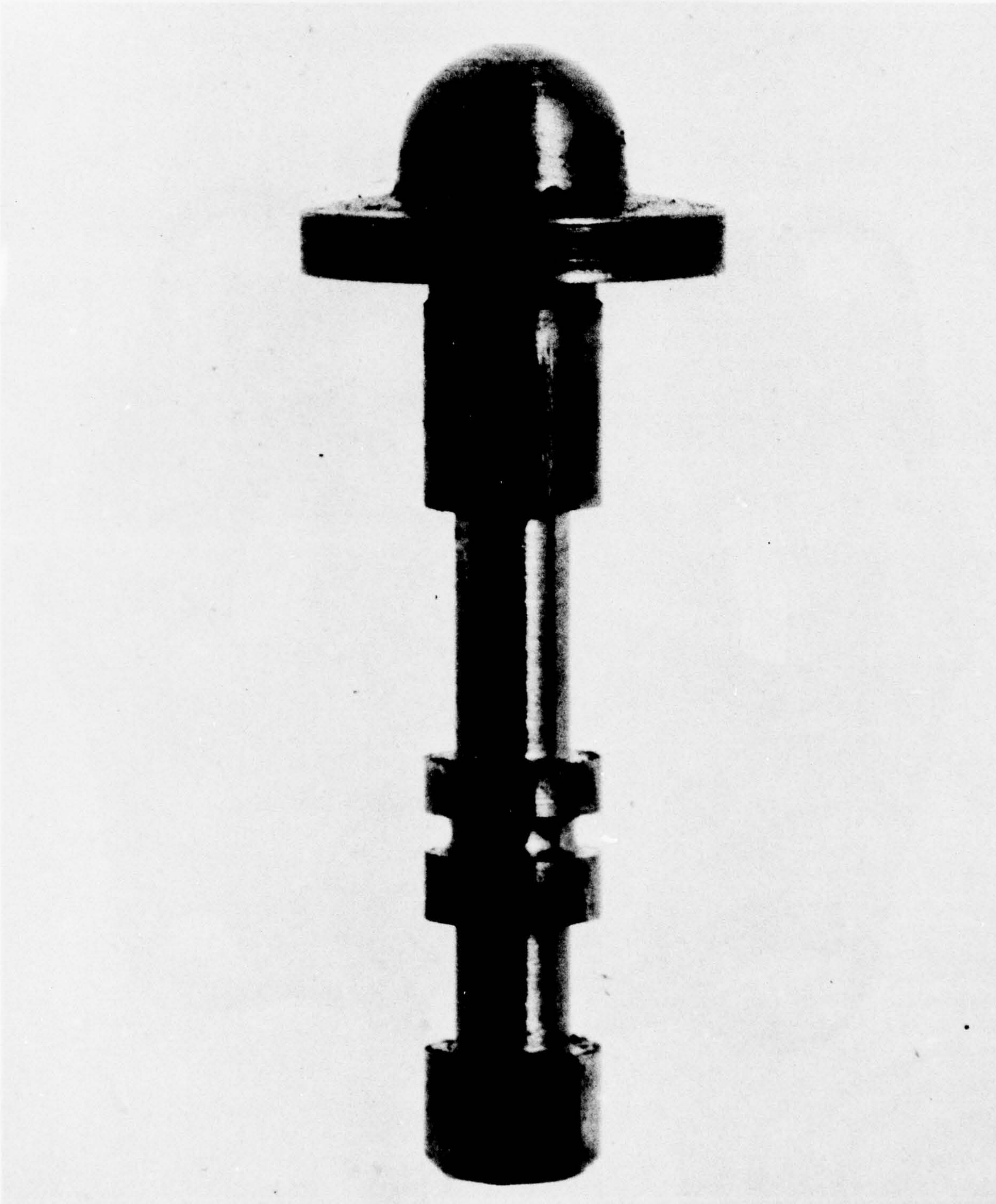

FIGURE 20 - Pilot Valve After Test

FIGURE 21 - Plate Retainer After Test

TABLE I. ANTIWEAR PROPERTIES OF TETRACHLOROPHENYLMETHYL SILOXANE FLUID

Wt. % Dibutyl Chlorendate	Wear Scar Diameter (mm)*		
	348°K (167°F)	450°K (350°F)	478°K (400°F)
0	1.30	**	**
1	1.10	**	**
2	0.69	1.38	**
3	0.76	1.02	1.01
4	0.82	0.98	1.05
5	0.96	1.01	1.06

* Shell Four Ball Wear Test: ASTM Method D 2266, 40 kg Load, 1200 rpm, 1h, 52100 steel balls

** Could not be determined due to excessive vibration of test apparatus indicating extremely poor antiwear properties

TABLE II. PROPERTIES OF EXPERIMENTAL FIRE-RESISTANT HYDRAULIC FLUID NADRAUL MS-6

Property	Test Method	Value	
Composition			
Base Fluid		96 wt % tetrachlorophenyl-methyl siloxane	
Antiwear Additive		4 wt % dibutyl chlorendate	
Density, 298°K (77°F)	ASTM D287	1.04 g/cm^3	
Viscosity	ASTM D-445		
478°K (400°F)		5.0 mm^2/s (5.0 cs)	
372°K (210°F)		19.3 mm^2/s (19.3 cs)	
311°K (100°F)		57.1 mm^2/s (57.1 cs)	
233°K (-40°F)		1,290 mm^2/s (1290 cs)	
219°K (-65°F)		2,780 mm^2/s (2780 cs)	
Steel on Steel Wear (40kg)	ASTM D-2266		
(52100 steel)			
348°K (167°F)		0.82 mm	
450°K (350°F)		0.98 mm	
478°K (400°F)		1.05 mm	
(M-10 steel)			
348°K (167°F)		0.85 mm	
478°K (400°F)		0.85 mm	
Flammability			
Flash point	ASTM D-92	550°K (530°F)	
Fire point	ASTM D-92	616°K (650°F)	
Wick test	AMS-3150C	100+ cycles	
Autoignition	ASTM-D2155	672°K (750°F)	
High pressure spray	FTS-791-6052	No ignition	
Low pressure spray	AMS-3150C	Extinguishes fire	
Flame propagation	MIL-H-83282	No ignition	
Oxidation-Corrosion	FTS-791-5308		
168h		478°K (400°F)	450°K (350°F)
ΔViscosity, 311°K (100°F)		+13.2%	+0.02%
Acid No. Change mgKOH/g		+0.08	+0.03
Metal Wt. Change mg/cm^2			
Cu		-1.0	-0.33
Al		+0.02	-0.03
Mg		-0.02	-0.04
Fe		+0.01	-0.02
Ag		+0.04	---
Insolubles or gum		None	None

TABLE II
(Continued)

Property	Test Method	Value	
Thermal Stability	FTS-791-5308		
168h, 478°K (400°F)	Modified to use N_2 instead of O_2	Metals	No metals
ΔViscosity, 311°K (100°F)		+4.7%	+7.1%
Acid No. Change mgKOH/g		+0.08	+0.18
Insolubles or gum		None	None
Rubber Swell, 168h	FTS-791-3603		
STD "L", 394°K (250°F)		+5.0%	
Viton, 343°K (158°F)		+0.7%	
408°K (275°F)		+0.8%	
450°K (350°F)		+1.3%	
Copper Corrosion, 478°K (400°F) 100h	ASTM D130	Pass	
Shear Stability	MIL-H-5606		
ΔViscosity @ 311°K (100°F)		+2.0%	
Acid No Increase mgKOH/g		0.00	
Pour Point	ASTM D97	<211°K (<-80°F)	
Low Temp Stability	FTS-791-3459		
72h, 219°K (-65°F)		Pass	
Foaming Tendency	ASTM D892		
298°K (77°F), 5 min.		0.400 dm^3 (400 ml)	
Collapse time		10 min.	
372°K (210°F), 5 min.		0.380 dm^3 (380 ml)	
Collapse time		10 min.	
298°K (77°F), 5 min.		0.350 dm^3 (350 ml)	
Collapse time		9 min.	
Hydrolytic Stability	ASTM D2619		
48h, 380°K (225°F)			
Δwt. of Cu		0.00 mg	
ΔViscosity, 311°K (100°F)		-0.017%	
Total acidity H_2O layer		1.94 mgKOH	
Acid No. organic layer		0.03 mg KOH/g	

TABLE III. EFFECT OF ESTER CONTENT ON PROPERTIES OF ALKYL-ESTER SILOXANE FLUID

Property	Test Method	10% Ester	18% Ester
Density, 298°K (77°F)	ASTM D287	0.876 g/cm^3	0.891 g/cm^3
Viscosity, mm^2/s (CS)	ASTM D445		
311°K (100°F)		17.4	33.2
233°K (-40°F)		1010	3040
219°K (-65°F)		4055	14,000
Flash Point	ASTM D92	512°K (480°F)	564°K (555°F)
Fire Point	ASTM D92	544°K (520°F)	597°K (615°F)
Wick Test, Cycles	AMS-3150C	17	100+
Steel on Steel Wear, mm 40kg, 1200 RPM, 1h	ASTM D2266		
348°K (167°F)		0.90	0.77
422°K (300°F)		1.04	1.04
450°K (350°F)		1.86	1.20
478°K (400°F)		2.0	1.74

TABLE IV. PROPERTIES OF EXPERIMENTAL FLUID "750"

Property	Test Method	Value	
Composition			
Base Fluid		97.5 wt % Alkyl-Ester Siloxane (18% Ester)	
Additives		2.0 wt % Trioctyl Phosphate 0.5% Tris (2-Chloroethyl) Phosphite	
Density, 298°K (77°F)	ASTM D287	0.890 g/cm^3	
Viscosity, mm^2/s (CS)	ASTM D445		
372°K (210°F)		6.8	
311°K (100°F)		32.4	
233°K (-40°F)		2900	
219°K (-65°F)		12,700	
Steel on Steel Wear mm	ASTM D2266		
40 kg, 1200 RPM, 1h			
348°K (167°F)		0.65	
422°K (300°F)		0.80	
450°K (350°F)		1.09	
478°K (400°F)		1.30	
Flammability			
Flash Point	ASTM D92	561°K (550°F)	
Fire Point	ASTM D92	589°K (600°F)	
Autoignition	ASTM D2155	672°K (750°F)	
High Pressure Spray	FTS-791-6052	Ignites, Self Extinguishes	
Wick Test, Cycles	AMS-3150C	Erratic Test Results 30 to 100+	
Oxidation-Corrosion 168h	FTS-791-5308	408°K (275°F)	450°K (350°F)
ΔViscosity, 311°K (100°K)		+1.2%	+818%
Acid No Change		-0.21	+11.1
Metal Wt Change (mg/cm^2)			
Cu		-0.08	+1.68
Al		+0.02	-0.03
Mg		+0.09	+0.08
Fe		+0.02	-0.02
Cd		0.0	--

TABLE IV
(Continued)

Property	Test Method	Value	
Rubber Swell 168h	FTS-791-3603		
"STD" L, 394°K (250°F)		+2.1%	
Fluoroelastomer, 343°K (158°F)		+0.5%	
408°K (275°F)		+0.6%	
450°K (350°F)		+0.6%	
Copper Corrosion, 450°K (350°F) 100h	ASTM D130	Pass	
Shear Stability	MIL-H-5606		
Δ Viscosity, 311°K (100°F)		+12.3%	
Acid No Change	—	0.00	
Pour Point	ASTM 097	< 211°K (< -80°F)	
			Amount after 600s
Foaming Characteristics	ASTM D892	300s Aeration	Collapse
298°K (77°F)		130 ml	0 ml
372°K (210°F)		100 ml	0 ml
298°K (77°F)		125 ml	0 ml
Hydrolytic Stability 48h, 380°K (225°F)	ASTM D2619		
Δ Wt. of Cu			-0.009 mg
Δ Viscosity, 311°K (100°F)			-3.2%
Total Acidity H_2O Layer			204.1 mg KOH
Acid No. Organic Layer			1.4 mg KOH/g

TABLE V. HYDRAULIC PUMP-LOOP CIRCUIT OPERATING DATA

AVERAGE FLUID TEMPERATURE	
Pump Inlet	412°K (282°F)
Pump Discharge	414°K (286°F)
System	422°K (299°F)
Case Drain	405°K (270°F)
Return Line	429°K (313°F)
Reservoir	412°K (282°F)
FLOW RATE	
Pump Discharge	0.250 dm^3/s (4 gpm)
Pump Case Drain	0.0025 dm^3/s (0.04 gpm)
AVERAGE FLUID PRESSURE	
Pump Discharge	19.99 MPa (2900 PSI)
Pump Inlet	193.0 kPa (28 PSI)
Pump Case Drain	386.1 kPa (56 PSI)
Actuator	18.23 MPa (2650 PSI)
PUMP SPEED	4050 rpm
TOTAL PUMP TEST TIME	500h
NUMBER OF ACTUATION CYCLES	81,341
FLUID QUANTITY	
Initial	12.20 dm^3 (12,200 ml)
Total Added During Test	4.35 dm^3 (4350 ml)

TABLE VI. PRETEST AND POST-TEST PUMP CALIBRATION DATA

Pump Spee- (rpm)	Pump Pressure MPa	(PSI)	Pump Discharge Flow Pretest dm^3/s	Pretest (gpm)	Post-Test dm^3/s	Post-Test (gpm)
1000	5.17	(750)	0.12	(1.9)	0.11	(1.8)
	10.34	(1500)	0.11	(1.7)	0.11	(1.8)
	15.51	(2250)	0.11	(1.7)	0.11	(1.8)
	19.30	(2800)	0.10	(1.6)	0.11	(1.7)
2000	5.17	(750)	0.23	(3.6)	0.22	(3.5)
	10.34	(1500)	0.22	(3.5)	0.22	(3.5)
	15.51	(2250)	0.23	(3.5)	0.22	(3.5)
	19.30	(2800)	0.21	(3.4)	0.21	(3.4)
3000	5.17	(750)	0.31	(5.0)	0.31	(4.9)
	10.34	(1500)	0.31	(5.0)	0.31	(4.9)
	15.51	(2250)	0.30	(4.8)	0.30	(4.8)
	19.30	(2800)	0.30	(4.8)	0.30	(4.8)
4000	5.17	(750)	0.41	(6.6)	0.41	(6.5)
	10.34	(1500)	0.41	(6.5)	0.41	(6.5)
	15.51	(2250)	0.40	(6.4)	0.40	(6.4)
	19.30	(2800)	0.40	(6.4)	0.40	(6.4)

TABLE VII. RECORD OF ACTUATOR SEAL LEAKAGE

Pump Operating Time (h)	Leakage Measurement Period (h)	Actuator Cycles	Amount of Leakage (ml) $405^{\circ}K$ ($270^{\circ}F$) -$414^{\circ}K$ ($285^{\circ}F$) Douglas No. 1	Douglas No. 2	Douglas No. 3
15.5	7.5	2,855	---*	Trace	Trace
21.0	5.5	3,705	---	Trace	Trace
25.5	4.5	4,320	---	Trace	Trace
33.0	7.5	5,560	---	Trace	Trace
34.5	1.5	5,744	---	Trace	Trace
42.0	7.5	6,990	---	Trace	Trace
48.5	6.5	8,063	---	Trace	Trace
51.0	2.5	9,009	---	1	1
53.5	2.5	9,295	---	1	1
61.0	7.5	10,588	---	2	2
68.0	7.0	11,820	---	2.5	2.5
75.0	7.0	12,990	---	3	2.5
80.0	5.5	13,946	---	5	2.5
86.0	5.5	14,840	---	5	2.5
93.0	7.0	16,016	---	5	2.5
99.0	6.0	17,008	---	3.5	2
106.5	7.5	18,220	---	4.5	2
109.0	2.5	18,595	---	2	1
112.0	3.0	19,015	---	3	1
119.5	7.5	20,280	---	5	1.5
127.0	7.5	21,520	---	5	2
134.5	7.5	22,685	---	5	2
142.0	7.5	23,875	---	4	2
149.0	7.0	24,980	3	4.5	1.5
156.5	7.5	26,275	2	5	1.5
164.0	7.5	27,440	4	4	1.5
170.0	6.0	28,425	4	3	1.5
177.5	7.5	29,720	5	3.5	1
182.5	5.0	30,545	5	3	1
189.5	7.0	31,720	5	3.5	1.5
196.5	7.0	32,915	5.5	4	1.5
203.5	7.0	34,140	5	4	1.5
211.0	7.5	35,440	5	4	1.5
218.5	7.5	36,715	5	4	1.5
226.0	7.5	37,935	5	4	1.5
229.0	3.0	38,450	3	2	---
236.5	7.5	39,705	6	5	1.5
243.5	7.0	40,920	6	5	1.5
251.0	7.5	42,210	5	3	1.5
258.5	7.5	43,525	5	3	1.5
262.0	3.5	44,080	2	3	---
269.5	7.5	45,295	4	5	1.5

TABLE VII
(Continued)

			Amount of Leakage (ml) $405^{o}K$ $(270^{o}F)$ $-414^{o}K$ $(285^{o}F)$		
Pump Operating Time (h)	Leakage Measurement Period (h)	Actuator Cycles	Douglas No. 1	Douglas No. 2	Douglas No. 3
277.0	7.5	46,550	4	5	1.5
284.5	7.5	47,785	4	5.5	1.5
289.5	5.0	48,630	4	---*	1.5
294.5	5.0	49,485	4	---	1.5
300.5	6.0	50,500	4	---	1.5
308.0	7.5	51,730	4	---	1.5
315.5	7.5	52,945	4	---	1.5
323.0	7.5	54,130	4.5	---	1.5
329.0	6.0	55,110	4.5	---	1.5
336.5	7.5	56,310	4.5	---	1.5
343.5	7.0	57,460	4.5	---	1.5
351.0	7.5	58,720	4.5	---	1.5
358.5	7.5	59,900	4.5	---	1.5
366.0	7.5	61,080	4	---	1
373.5	7.5	62,275	4	---	1
381.0	7.5	63,430	4	---	1
388.5	7.5	64,630	4	---	1
396.0	7.5	65,820	4	---	1
403.5	7.5	66,905	4	---	1
407.0	3.5	67,385	2	---	0.5
414.5	7.5	68,520	4	---	1
422.0	7.5	69,660	4	---	1
427.5	5.5	70,234	4	---	1
435.0	7.5	71,540	4	---	1
442.5	7.5	72,720	4	---	1
450.0	7.5	73,813	4	---	1
457.5	7.5	74,960	4	---	1
464.5	7.0	76,015	4	---	1
472.0	7.5	77,107	4	---	1
479.5	7.5	78,230	4	---	1
481.0	1.5	78,510	0.5	---	0
488.5	7.5	79,615	4	---	1
496.0	7.5	80,765	4	---	1
500.0	4.0	81,341	2	---	0.5

* Actuator removed from system due to malfunction

TABLE VIII. RECORD OF PRESSURE DROP ACROSS FILTERS AFTER EACH START UP

(PUMP SPEED 1500 RPM; FLOW RATE MAIN BY-PASS $0.19\ dm^3/s$ (3 gpm))

Pump Operating Time (h)	System Temperature F	K	Pump Discharge Pressure PSI	MPa	△P Return Line PSI	kPa	△P Case Drain PSI	kPa
0	100	301	1500	10.34	15	103	0	0
5.0	115	319	1800	12.41	20	138	0	0
12.5	104	313	2450	16.89	28	193	0	0
17.5	120	322	2750	18.96	30*	207*	0	0
22.0	128	326	2850	19.65	10	68.9	0	0
29.5	100	301	2975	20.51	11	75.8	0	0
31.0	195	364	2975	20.51	6	41.4	0	0
38.5	100	301	2700	18.61	20	137.9	0	0
45.0	175	352	2750	18.96	22*	151.7*	0	0
51.5	205	369	2900	19.99	2	13.8	0.5	3.5
54.0	210	372	2890	19.92	2	13.8	0.5	3.5
61.5	205	369	2900	19.99	5	34.5	0.5	3.5
68.5	208	371	2900	19.99	10	68.9	1	6.9
75.5	218	376	2925	20.17	12	82.7	0.5	3.5
81.0	190	361	2900	19.99	45*	310*	2	13.8
81.0	210	372	2940	20.27	1	6.9	1	6.9
86.5	210	372	2940	20.27	2	13.8	1	6.9
93.5	200	366	2950	20.34	1	6.9	1	6.9
99.0	210	372	2925	20.17	2	13.8	1	6.9
106.5	208	371	2925	20.17	2	13.8	1	6.9
109.0	230	383	2875	19.82	3	20.7	1	6.9
112.0	225	380	2875	19.82	3	20.7	1	6.9
129.5	220	377	2900	19.99	3	20.7	1	6.9
127.0	220	377	2900	19.99	4	27.6	1	6.9
134.5	210	372	2975	20.51	5	34.5	1**	6.9**
142.0	210	372	2950	20.34	0	0	0	0
149.0	210	372	2975	20.51	7	48.3	1	6.9
156.5	230	383	2950	20.34	11	75.8	1	6.9
164.0	150	339	2900	19.99	50*	345*	1	6.9
164.0	155	341	3000	20.68	3	20.7	1	6.9
170.0	158	343	2925	20.17	3	20.7	1	6.9
177.5	158	343	2925	20.17	3	20.7	1	6.9
182.5	145	336	2925	20.17	4	27.6	1	6.9
189.5	158	336	3000	20.68	5	34.5	1	6.9
196.5	120	322	3000	20.68	15	103	1	6.9
203.5	130	327	3025	20.85	15	103	1	6.9
211.0	130	327	3050	21.03	18	124	1	6.9
218.5	130	327	3025	20.85	23	159	1	6.9
226.0	130	327	3025	20.85	23	159	1	6.9

TABLE VIII
(Continued)

(PUMP SPEED 1500 RPM; FLOW RATE MAIN BY-PASS
0.19 dm^3/s (3 gpm))

Pump Operating Time	System Temperature		Pump Discharge Pressure		ΔP Return Line		ΔP Case Drain	
(h)	F	K	PSI	MPa	PSI	kPa	PSI	kPa
229.0	125	325	3025	20.85	40	276	1	6.9
236.5	125	325	3050	21.03	50*	345*	1	6.9
236.5	145	336	3000	20.68	3	20.7	1	6.9
243.5	135	330	3025	20.85	5	345	1	6.9
251.5	125	325	3025	20.85	8	55.2	1	6.9
258.5	230	383	2950	20.34	9	62.1	1	6.9
262.0	200	366	3025	20.85	8	55.2	0.5	3.5
269.5	180	355	3000	20.68	14	96.5	1	6.9
277.0	215	375	2950	20.34	16	110	0.5	3.5
284.5	286	414	2925	20.17	23*	159*	0.5	3.5
284.5	170	350	2950	20.34	4	27.6	1	6.9
289.5	290	416	2950	20.34	12*	82.7*	1	6.9
289.5	215	375	2925	20.17	1	6.9	0.5	3.5
294.5	180	355	2925	20.17	1	6.9	1	6.9
300.5	185	358	2950	20.34	2	13.8	0.5	3.5
308.0	190	361	2950	20.34	2	13.8	1	6.9
315.5	225	380	2950	20.34	2	13.8	1	6.9
323.0	220	377	2950	20.34	2	13.8	1	6.9
329.0	205	369	2950	20.34	2	13.8	1	6.9
336.5	165	347	2950	20.34	2	13.8	0	0
343.5	205	369	2950	20.34	2	13.8	0	0
351.0	170	350	2975	20.51	2	13.8	0	0
358.5	205	369	2950	20.34	2	13.8	0	0
366.0	215	375	2950	20.34	2	13.8	0	0
373.5	218	376	2950	20.34	2	13.8	0	0
381.0	170	350	2950	20.34	3	20.7	0	0
288.5	215	375	2950	20.34	2	13.8	0	0
396.0	166	347	2950	20.34	4	27.6	0	0
413.5	183	357	2950	20.34	3	20.7	0	0
407.0	188	360	2950	20.34	3	20.7	0	0
414.5	168	349	2950	20.34	4	27.6	0	0
422.0	245	391	2925	20.17	2	13.8	0	0
427.5	225	380	2950	20.34	2	13.8	0	0
435.0	218	376	2925	20.17	3	20.7	0	0
442.5	218	376	2925	20.17	4	27.6	1	6.9
450.0	160	344	2975	20.51	8	55.2	0	0
457.5	178	351	2950	20.34	9	62.1	0	0
464.5	225	380	2925	20.17	7	48.3	0	0
472.0	198	365	2925	20.17	9	62.1	0	0
479.5	215	375	2900	19.99	15	103	0	0
481.0	232	384	2900	19.99	14	96.5	1	6.9
488.5	232	384	2900	19.99	19	131	0	0
496.0	215	375	2925	20.17	22	152	0	0

*Filter element replaced due to high pressure build-up
**Filter element check for metallic particles and replaced

TABLE IX. PUMP TEST FLUID SAMPLE PROPERTIES

Sample Test Hours	Viscosity (1) 311°K (100°F) mm^2/s or (cs)	Wear Scar (2) mm 478°K (400°F)	Acid Number (3) mg KOH/g	Wick (4) Flammability Cycles
0	54.4	1.00	0.062	100+
5	54.6	1.02	0.087	
10	54.4	1.08	0.073	
25	54.4	1.01	0.059	
50	58.5	1.06	0.071	
75	57.3	1.04	0.059	100+
100	55.0	1.03	0.071	
150	54.4	1.02	0.098	
200	55.2	1.00	0.076	
250	54.5	0.99	0.071	100+
300	55.8	0.98	0.073	
350	57.0	0.97	0.069	
400	55.5	0.99	0.067	
450	55.2	0.99	0.069	
500	54.8	1.02	0.071	100+

1. ASTM Method D445

2. ASTM Method D2266 40 kg, 1200 rpm, 1h, 52100 Steel Balls

3. ASTM Method D664

4. FTS-791-352

TABLE X. MS-6 FLUID PROPERTIES BEFORE AND AFTER PUMP TEST EVALUATION

Property	Test Method	Before Test	After Test
Density 298°K (77°F)	ASTM D287	1.035 g/cm^3	1.034 g/cm^3
Viscosity	ASTM D445		
372°K (210°F)		18.6 mm^2/s	--
311°K (100°F)		54.4 mm^2/s	55.3
233°K (-40°F)		1023 mm^2/s	1002
219°K (-65°F)		2722 mm^2/s	2831
Pour Point	ASTM D97	211°K (-80°F)	211°K (-80°F)
Fire Resistance			
Wick Test, Cycles	AMS 3150C	100+	100+
Flash Point	ASTM D92	550°K (530°F)	552°K (535°F)
Fire Point	ASTM D92	616°K (650°F)	616°K (650°F)
Autoignition	ASTM D2155	672°K (750°F)	616°K (730°F)
High Pressure-Spray Ignition	FTS-791-6052	No ignition	No ignition
Steel on Steel Wear	ASTM D2266		
52100 Steel, 40 Kg			
348°K (167°F)		0.71 mm	0.70 mm
450°K (350°F)		0.99	0.98
478°K (400°F)		1.02	1.02
Acid Number	ASTM D974	0.062 $\frac{mg\ KOH}{g}$	0.067 $\frac{mg\ KOH}{g}$
Oxidation-Corrosion	FTS-791-5308		
168h, 478°K (400°F)			
Δ Viscosity, 311°K (100°F)		+18.9%	+12.8%
Acid No. Change		+0.10 $\frac{mg\ KOH}{g}$	+0.21 $\frac{mg\ KOH}{g}$

TABLE XI. PUMP FRICTION ELEMENT DIMENSIONAL AND WEIGHT CHANGES

Element	Weight Change mg *	Weight Change mg **	Dimensional Change mm (in.)
Piston			
1	-20.0	-23.8	
2	-23.8	-28.6	No dimensional change when measured to fourth decimal place in inches
3	+16.5	-29.7	
4	+ 5.1	-24.3	
5	-23.7	-29.0	
6	-23.0	-26.2	
7	-21.5	-26.0	
Cylinder Block	+8.300		
Bore No.			
1			(+0.0001)
2			(+0.0002)
3			(0.0000)
4			(+0.0001)
5			(+0.0000)
6			(0.0000)
7			(+0.0001)
Shoe Wear Plate	-1.4		(0.0000)
Shoe Held-Down Plate	-3.8		(-0.0002)
Shoe Hold-Down Plate Retainer	* -3.4	** -25.2	(0.0000)
Pilot Valve	----		(0.0000)
Control Piston	----		(-0.0001)

*Weight taken on element on disassembly from pump
**Weight taken on element after cleaning

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